Abstract- Metal-on-ultra high molecular weight polyethylene (UHMWPE) total hip replacement (THR) has been the most popular and clinically successful hip prosthesis to date. The long-term performance of THR depends on both the tribological characteristics and biomechanical behaviour of the prosthesis. Experimental approaches have the limitations of high costs, time-consuming and complex. Therefore, a simplified finite element model was developed to compare the measured contact areas and contact pressures from experimental model. The contact areas on the articulating surface of polyethylene cup under different loads were measured experimentally in self-made joint simulator and then maximum contact pressures were calculated from these measurements according to Hertzian Contact Theory. Good agreements of contact areas and contact pressures between finite element predictions from the simplified model and experimental measurements and calculations were obtained. This indicated that the simplifications and assumptions made for the finite element model were reasonable and finite element predictions from the simplified model were valid.

Keywords- Total Hip Replacement, Metal-on-Polyethylene, Contact Mechanics.

I. INTRODUCTION

Total Hip Replacement (THR) is one of the best solutions for hip joint diseases and the most successful surgical interventions in the orthopaedics field. Several material combinations for hip joint replacements have been introduced, including metal-on-polyethylene (MoP), ceramic-on-polyethylene (CoP), metal-on-metal (MoM), ceramic-on-ceramic (CoC) and ceramic-on-metal (CoM). Each of them has its own benefits and limitations. Due to its durability and performance, MoP has been the leading bearing material combination chosen by surgeons for at least 30 years, and remains the gold standard for hip joint replacements today. Hip replacements can fail for a variety of reasons and clinical outcomes with new designs and materials are not always as expected [1]. For this reason, pre-clinical testing and evaluation of the THR are necessary and very important. Experimental tests are developed to the performance of these devices [2,3]. However, experimental studies are complex, time consuming and expensive to conduct. Alternatively, computational simulation is an effective solution for assessing and evaluating the performance of THR [4]. The computational analysis of contact mechanics of the THR is very important. The investigation of the contact mechanics of hip replacements is an important step to optimize the implant design, materials, surgical parameters, and provide better understanding of the long-term performance and success of the implants [5,6].

The direct validation for the anatomic FE model is a challenge as it is difficult to obtain a bony human pelvis for the experiments. Therefore, a simplified FE model of a MoP THR consist of a femoral head and a cup was developed for the purpose of investigating its contact mechanics under adverse conditions. The aim of this study was to evaluate the contact mechanics of the MoP THR by comparing the contact areas and contact pressures on the articulating surface between the experimental measurement and simple FE model predictions.

II. MATERIALS AND METHODS

Stainless steel femoral head and polyethylene acetabular cup specimens were manufactured in local workshop (Fig.1a). The nominal diameters of the femoral head (R₁), and inner surface of the acetabular cup (R₂) were 28 mm and 28.1 mm respectively, giving a radial clearance of 0.05 mm between the femoral head and acetabular cup. In order to simplify the experimental validation process, only the ball and the specimens modelled for FE study. Based on the assumption that such simplification would not change the model predictions with respect to the contact mechanics of total hip replacements [8]. The verification of the simplified model was then carried out by comparing the contact areas on the articulating surface between the experimental measurements and FE predictions.

2.1. Experimental Study

Purposely designed moulds were used to attach the ball and cup specimens on a self-made multi joint simulator as shown in Fig.1b. To determine the contact areas on cup specimen, Indians ink was applied on contact surfaces. In the simulator the
femoral head was replaced above the cup and the cup was mounted on an inclined block (angle of inclination of 23°) respect to its anatomical position [9]. Three different loads of 500, 1000 and 1500 were applied through the ball on the cup. The maximum load of 1500 N considered in this study corresponds to approximately 2 times body weight for an average weight of 80 kg [10]. To remove the Indian ink from contact surface, ±2° of internal-external rotation was applied to cup specimen and the load was immediately removed after 100 cycles for each test. The maximum contact pressure was calculated according to Hertzian Contact theory (in case of a sinusoidal repartition of pressure) is:

\[ p_{\text{max}} = \frac{3F}{2\pi a^2} \]

where \( p_{\text{max}} \) is maximum pressure at the centre of the contact, \( F \) is applied load, \( a \) is contact radius and so \( \pi a^2 \) is projected contact area which is measured from the experiments.

2.2. Finite Element Modelling
A three-dimensional FE model was developed to simulate the contact mechanics of metal-polyethylene total hip system. The ball and the cup materials in the FE model were modelled as homogenous, isotropic and linear elastic. The cup was positioned with an inclination angle of 23° same as in experimental study (Fig.2). The nodes on the bottom surface of the cup were fully fixed to represent the fixation of the cup to the mould in the experiment. This assumption is valid since the elastic modulus of the mould is at least 2-3 times that of the polyethylene [10]. A sliding contact formulation was applied on the articulating surface between ball and cup, with friction coefficient of 0.15 [11]. Vertical loads of 500, 1000 and 1500 N, which were applied in the experimental tests, were applied at the centre of the femoral head.

III. RESULTS AND DISCUSSION

Similar contact area patterns were observed between the experimental measurements and FE predictions (Fig.3), although there were slight differences in the contact area values (Fig.4). For all loading conditions, the differences of contact areas between the experimental measurements and FE predictions were within 5.4%. An increased load from 500 N to 1500 N resulted in an increased contact areas of approximately 12% and 22% for experimental measurements and FE predictions, respectively.

For all loading conditions considered, the predicted area of contact pressure was located about the superior region of the cup in the loading direction (Fig.5). The differences of contact pressures between the experimental measurements and FE predictions were 2.8%, 4.7% and 5.3% for applied loads of 500 N, 1000 N and 1500 N, respectively (Fig.6).
Due to the difficulties in the experimental validation on a 3D anatomic FE models for metal on polyethylene total hip replacements, a simplified model consist of a cup and a femoral head was developed in this study. The validity of FE model was evaluated by directly comparing the contact areas between the experimental tests and FE predictions from the simplified model. A good agreement was obtained between the experimental measurements and FE predictions with respect to the contact area patterns and contact area magnitudes. This confirmed the validity of the simplified FE model to predict contact area, and provided great confidence in the validity of the simplified FE model to predict contact pressures. Simplications and assumptions in the simplified FE model did not influence the FE predictions of contact mechanics of metal on polyethylene THR [12]. Although the results of the FE modelling showed good agreement with the experimental measurements, studies of this nature are not without their limitations. Indeed, errors from several sources may affect the final results and need to be examined with caution. Firstly, the material properties of the polyethylene cup in the FE modelling was from manufacturer’s catalogue and considered as a linear elastic material which may be different from that used in the experimental tests. This is likely to be a major source of error. Although each test was run for a short time, the polyethylene specimens still showed a degree of viscoelastic behaviour which can result in creep and material flow away from the contact region [13], this may have a marked effect on the contact areas measured. However, in the FE predictions, the creep and viscoelasticity was not considered. Finally, only three experiments per polyethylene specimen were performed, it would have been desirable to conduct a series of experiments on each specimen and then take the average results to minimize the random errors. In spite the several limitations and error sources listed above, as well as other potential error sources which have not been evaluated, the present study produced exceptionally positive outcome. The FE modelling produced very reasonable predictions with respect to the contact areas and contact pressures when compared to experimental measurements. This gives a great confidence in the use of the model to study the clinical applications across the hip implants such as edge loading, microseparation etc., and to evaluate the new hip implants designs.

Previous studies have demonstrated that a change of the friction coefficient at the articulating surfaces between the femoral and acetabular components was found to have a negligible effect on the predicted contact pressure and contact area [5]. The friction coefficient for MoP was reported to range from 0.083 to 0.2 [14]. Ramero and colleagues demonstrated that the results obtained in the FE models with different friction coefficients were between the maximum and minimum values obtained in the experiment [15]. Based on these, the coefficient of friction of 0.15 was chosen for the FE model in the current study.

CONCLUSIONS

Both the experimental measurement and calculation of contact areas and contact pressures and the FE predictions of contact areas and contact pressures from simplified FE model have been carried out for MoP THR in this study. Good agreement of the contact areas and contact pressures have been found between the experimental measurements and FE predictions the simplified model. This indicated the validity of the simplified model to predict the contact mechanics of the MoP THR and encouraged to use to study the biomechanics of MoP THR under different conditions, especially adverse conditions in the future studies.

REFERENCES

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